TRACE FOSSILS OF THE ?EARLY ORDOVICIAN SARDINIA BAY FORMATION, TABLE MOUNTAIN GROUP

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(With 12 figures)

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ABSTRACT

Several sandstones in the 180 m thick Sardinia Bay Formation of the lower portion of the Table Mountain Group, contain trace fossils. Endichnial burrows are most common, including traces that resemble the genera *Ophiomorpha*, *Thalassinoides*, *Diplocraterion*, *Skolithos*, and *Fascifodina*. Hypichnial traces on the sole of one sandstone are tentatively identified as *Cruziana*. A number of enigmatic traces occur on bedding surfaces. Three trace fossil associations are recognized in the Sardinia Bay Formation. Two of these correspond broadly with the *Cruziana* and *Skolithos* ichnofacies models of Seilacher (1967) and Frey & Pemberton (1984), but differ significantly in detail. The differences are ascribed to reduced circulation resulting in anoxic conditions in parts of an ancient epeiric sea. Barren sandstone units in the Sardinia Bay strata represent former high-energy depositional environments and shifting substrates hostile to sediment-dwelling organisms. Pyritic trace-free mudrocks may have been deposited in biologically sterile parts of the epeiric sea.

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INTRODUCTION

LOCATION AND GENERAL GEOLOGY

The Sardinia Bay Formation crops out near Port Elizabeth in the vicinity of Sardinia Bay (Fig. 1). These strata represent part of the lowermost Table Mountain Group in the Port Elizabeth area. The probable base of the Table Mountain Group is represented by an outcrop of granite overlain by conglomerates containing boulders of granite and quartzite, which lies about 2 km west of Sardinia Bay. The thickness of strata separating these conglomerates and the base of the Sardinia Bay Formation is not known.

Rocks of the Sardinia Bay Formation occur on the northern limb of a major asymmetrical anticlinal structure in the Table Mountain Group formed in response to compressional forces directed from the south. There is evidence of a subsequent east–west compression in the Sardinia Bay area (Shone 1983: 65–71). Rocks of the Sardinia Bay Formation appear to have been subjected to low-grade load metamorphism prior to the folding episodes (De Swardt & Rowsell 1974; Shone 1983: 125).

Characteristic rock types are metaquartzites and phyllites. The emphasis on ichnology and sedimentology in this paper favours reference to them as sandstones and mudrocks.

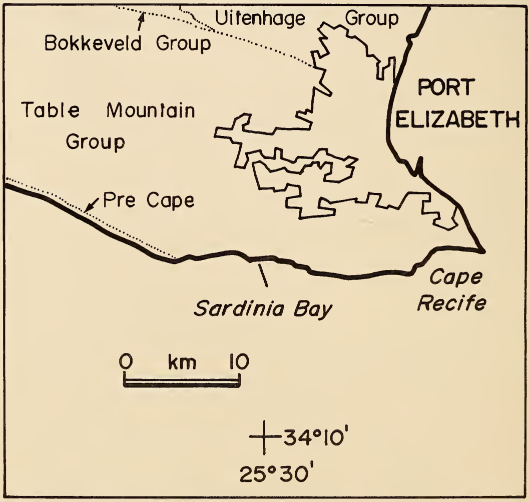

Fig. 1. Map showing location of Sardinia Bay.

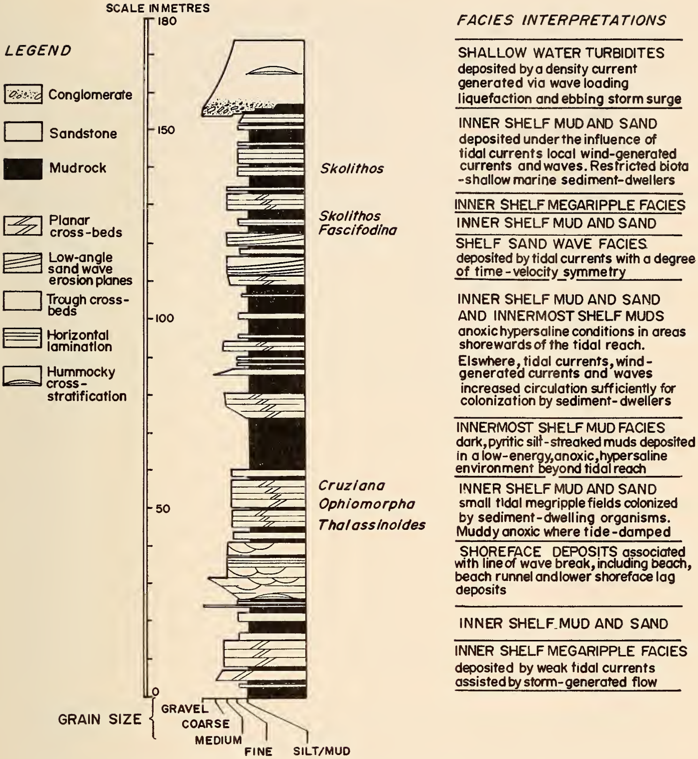
SCALE IN METRES
180
150
100
50
0
LEGEND
Conglomerate
Sandstone
Mudrock
Planar cross-beds
Low-angle sand wave erosion planes
Trough cross-beds
Horizontal lamination
Hummocky cross-stratification
GRAIN SIZE
GRAVEL
COARSE
MEDIUM
FINE
SILT/MUD
Skolithos
Skolithos
Fascifodina
Cruziana
Ophiomorpha
Thalassinoides
FACIES INTERPRETATIONS
SHALLOW WATER TURBIDITES deposited by a density current generated via wave loading liquefaction and ebbing storm surge
INNER SHELF MUD AND SAND deposited under the influence of tidal currents local wind-generated currents and waves. Restricted biota -shallow marine sediment-dwellers
INNER SHELF MEGARIPPLE FACIES
INNER SHELF MUD AND SAND
SHELF SAND WAVE FACIES deposited by tidal currents with a degree of time-velocity symmetry
INNER SHELF MUD AND SAND AND INNERMOST SHELF MUDS anoxic hypersaline conditions in areas shorewards of the tidal reach. Elswhere, tidal currents, wind-generated currents and waves increased circulation sufficiently for colonization by sediment-dwellers
INNERMOST SHELF MUD FACIES dark, pyritic silt-streaked muds deposited in a low-energy, anoxic, hypersaline environment beyond tidal reach
INNER SHELF MUD AND SAND small tidal megripple fields colonized by sediment-dwelling organisms. Muddy anoxic where tide-damped
SHOREFACE DEPOSITS associated with line of wave break, including beach, beach runnel and lower shoreface lag deposits
INNER SHELF MUD AND SAND
INNER SHELF MEGARIPPLE FACIES deposited by weak tidal currents assisted by storm-generated flow

Fig. 2. Simplified stratigraphic section of the Sardinia Bay Formation showing facies interpretations and units containing trace fossils.

VERTICAL FACIES CHANGES AND DEPOSITIONAL MODEL

The 180 m thick Sardinia Bay Formation (*sensu* Shone 1979, 1983) can be subdivided into a number of facies on the basis of geometry, lithology, sedimentary structures, trace fossils and palaeoflow data (Shone 1983, 1987). Figure 2 shows a simplified stratigraphic section and the corresponding facies interpretations. Bioturbated units, indicated by the generic names of the more important trace fossils (Fig. 2), are limited to planar cross-bedded sandstones attributed to the migration of small megaripples in an inner-shelf depositional environment.

Elsewhere, the sandstones are fossil free but contain sedimentary structures that denote high-energy hydraulic conditions normally associated with beaches, tidal sand-waves (cf. Allen 1980), storm-affected shelf floors, and ebbing storm-surge turbidity flows (Shone 1983, 1987).

AGE AND CORRELATION OF THE SARDINIA BAY FORMATION

The absolute age of the Sardinia Bay Formation is not known. On the basis of extremely tenuous correlation with the Graafwater Formation of the Western Cape (Rust *in* Tankard *et al.* 1982: 339), an Early Ordovician age is possible. Even if the Graafwater–Sardinia Bay correlation is untenable, the Sardinia Bay rocks are likely to be older than the Ashgillian age proposed for rocks of the Upper Table Mountain Group (cf. Cocks *et al.* 1970). The granite outcrops west of Sardinia Bay have not yet been dated but, if sufficiently fresh material can be obtained, a lower age limit for the Sardinia Bay Formation could be deduced. The absence of body fossils other than enigmatic stromatoporoid fragments (Shone 1983: 257–259) aggravates the dating problem still further.

DESCRIPTIONS OF TRACE FOSSILS

Classification of trace fossils cannot be accomplished in the same manner as zoological classification (Häntzschel 1975: W16), and trace fossil names are not recognized in the *International Code of Zoological Nomenclature* (Ekdale *et al.* 1984: 17). In the case of the Sardinia Bay Formation, the identities of the organisms responsible for producing the traces are not known; trace morphology is all that can be determined. Even so, individual traces can seldom be named with confidence and some of the trace fossils could represent hitherto undescribed forms. In certain instances, trace fossils in the Sardinia Bay Formation exceed the time ranges known for comparable ichnogenera from other strata. The descriptions that follow are set out in accordance with the problems outlined above.

?OPHIOMORPHA

Description

Large sub-cylindrical sand-filled vertical burrows with dark pyritic linings occur as endichnial traces in several sandstone horizons. Differential weathering of the lining temporarily exposes the burrow-fill in bas-relief, but eventually both burrow lining and fill are excavated leaving the bedding surface crowded with perpendicular holes (Fig. 3). These weathered-out burrows seldom exceed 4 cm in diameter and penetrate little more than 12 cm into the substrate. In a few examples relict mammilation of the linings can be discerned (Shone 1983: 241–242). No clearly defined branching of the tubes has been observed, but strata adjacent to the vertically burrowed horizons contain numerous branching sub-horizontal burrows of similar diameter.

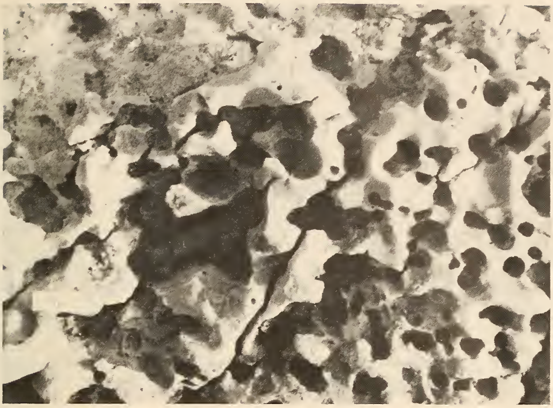

Fig. 3. Large-diameter vertical burrows. Differential weathering of the less resistant burrow-fill and lining results in a bedding surface crowded with holes perpendicular to bedding. Scale = 5 cm.

Interpretation

These vertical burrows are broadly similar to *Ophiomorpha* but lack the typical dichotomous branching of that ichnogenus. If the openings were more distinctly funnel-shaped and the plugged tubes curved in vertical section, *Monocraterion* might be a more plausible identification. The latter has a stratigraphic

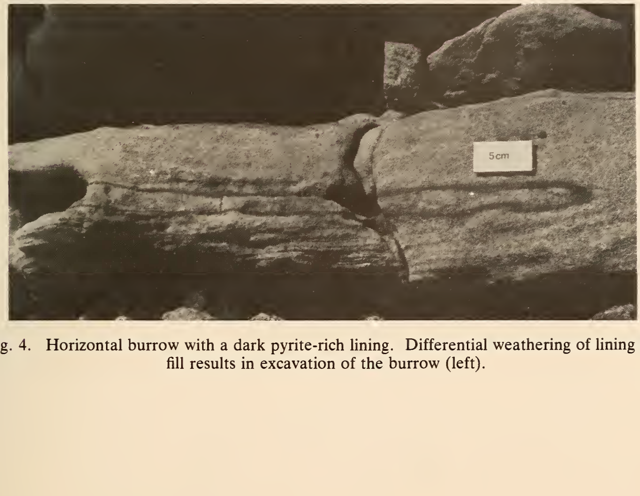

Fig. 4. Horizontal burrow with a dark pyrite-rich lining. Differential weathering of lining and fill results in excavation of the burrow (left).

time range from Cambrian to Jurassic (Häntzschel 1975: W84), whereas *Ophiomorpha* (Lower Permian–Recent) is typically associated with strata younger than the Sardinia Bay Formation (Häntzschel 1975: W85). *Ophiomorpha*-like structures in modern sediments are produced by callianassid decapods (Weimer & Hoyt 1964).

THALASSINOIDES SP.

Description

Smooth-walled sand-filled sub-horizontal to inclined burrows, with a lining of dark pyritic sand and circular to flattened-oval in cross-section (Fig. 4), occur in close stratigraphic proximity to beds permeated by large vertical *Ophiomorpha*-type burrows. These burrows often show repeated branching (Fig. 5). Burrow diameters range from 2 to 10 cm and individual shaft sections are up to 50 cm long. Inclined shafts may run parallel to foreset surfaces in the cross-bedded sandstone.

Interpretation

The sub-horizontal branching burrow systems described above are closely similar to *Thalassinoides* (Triassic–Recent), which are generally considered to be the dwelling burrows of callianassid decapods (Häntzschel 1975: W117) or crabs (Radwanski 1977: 233–235).

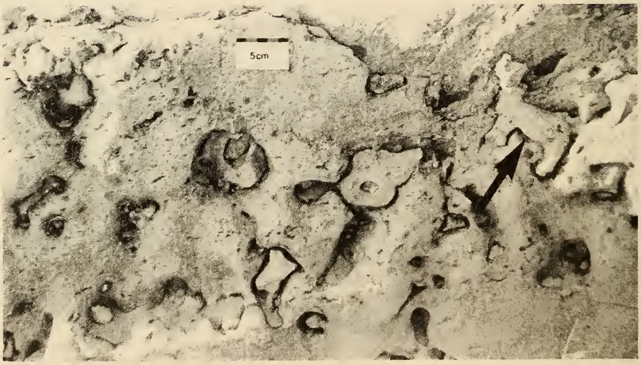

Fig. 5. Partly weathered burrows showing initial erosion of burrow lining and eventual excavation of fill and lining. Basal surface of a sandstone. Note the branching burrow (arrowed) which resembles *Thalassinoides*.

DIPLOCRATERION

Description

Spreiten demarcated by pyrite-rich laminae, indicating the former position of a U-tube, were found in a loose boulder of quartzite (Fig. 6). The exact stratigraphic position of this fragment has not been fixed but is probably close to the interval 30–60 m (see Fig. 2). Irregular U-tubes up to 2 cm in diameter, with the limbs of the tube up to 7 cm apart, occur 48 m from the base of the Sardinia Bay Formation. Spreiten can be discerned between the limbs of one U-tube (Fig. 7).

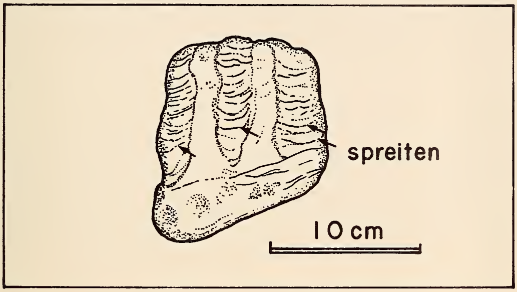

Fig. 6. Spreiten demarcating the former positions of U-tubes indicating upward migration of U-shaped burrows, probably *Diplocraterion*. Tracing from a loose boulder.

Interpretation

Figure 6 shows a typical example of *Diplocraterion* in which upward migration of the U-shaped burrow has occurred in response to sedimentation. The U-tubes themselves are not represented, possibly because of erosional truncation following sedimentation (cf. Goldring 1964, *in* Häntzschel 1975: W30). The irregular U-tubes shown in Figure 7 are less convincing examples of the ichnogenus. *Diplocraterion* is thought to be the dwelling trace of a suspension-feeding organism living in a high wave energy environment, and is known from strata of Cambrian to Cretaceous age (Häntzschel 1975: W62).

SKOLITHOS

Description

Millimetre-thin straight or gently-meandering sand-filled tubes, perpendicular to the bedding, occur in sandstones of the Upper Sardinia Bay Formation (see Fig. 2). Tube cross-sections are oval to roughly circular. The tubes are generally crowded to the extent that the internal lamination of the host bed is virtually destroyed (Fig. 8). Individual tubes appear to penetrate whole beds of up to 60 cm in thickness.

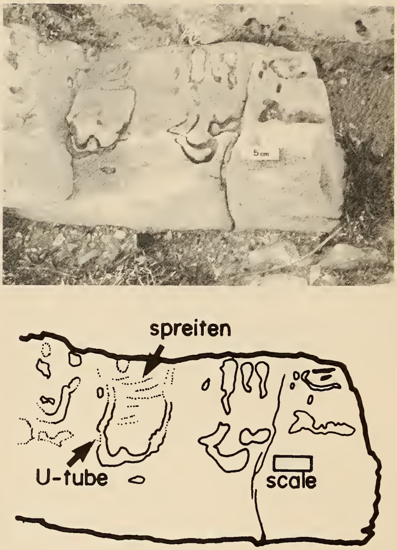

Fig. 7. Photograph (top) and tracing (bottom) showing an irregular U-tube with spreiten in a bioturbated sandstone.

Interpretation

These are probably *Skolithos* tubes (Upper Precambrian–Lower Cretaceous), usually attributed to the activities of marine worms but of uncertain origin (Häntzschel 1975: W108). *Skolithos* tubes are widespread in other Table Mountain Group outcrops (Rust 1967, 1973, 1977; Cocks *et al.* 1970: 603).

THIN VERMIFORM SAND-FILLED TUBES

Description

Vermiform sand-filled tubes, up to 1 cm in diameter and oval to circular in cross-section, occur in spaghetti-like masses towards the bases of thin sandstone beds (Fig. 9) in the Upper Sardinia Bay Formation. Individual tubes tend to straighten and become sub-vertical upwards.

Interpretation

The vermiform traces described above resemble lower parts of the ichnogenus *Fascifodina*, the upper parts of which, including the master-shaft, have been removed by erosion (cf. Häntzschel 1975: W63, fig. 3). *Fascifodina* is,

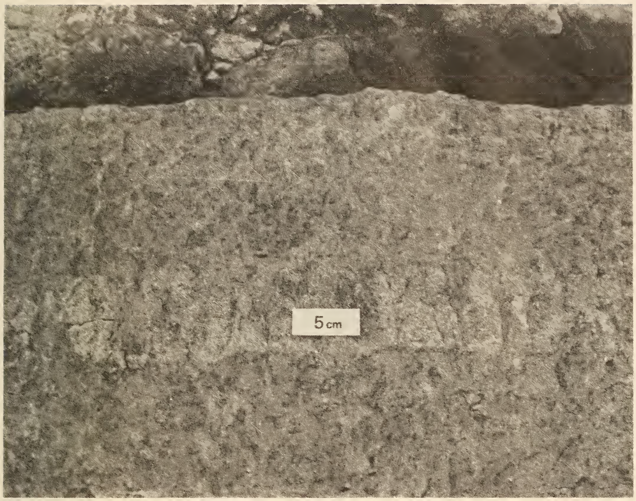

Fig. 8. Crowded *Skolithos* tubes in a quartzitic sandstone that has acquired massive texture as a result of the bioturbation.

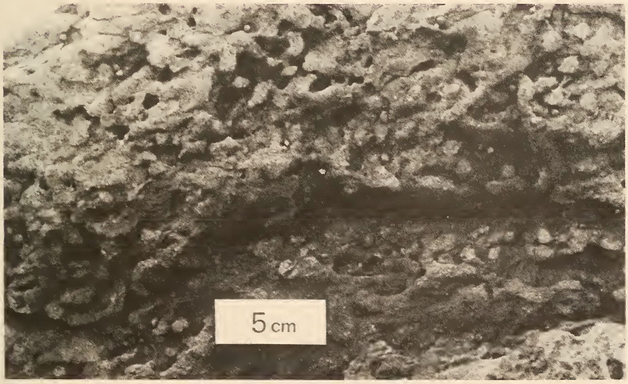

Fig. 9. Vermiform sand-filled tubes resembling *Fascifodina* on the basal surface of a sandstone, Upper Sardinia Bay Formation.

however, more usually identified by the presence of horseshoe-shaped groups of vermiform epireliefs (Häntzschel 1975). The vermiform burrows from the Sardinia Bay Formation could also be the result of interfering *Chondrites* burrows, but apparently lack the repeated branching characteristic of *Chondrites*. *Fascifodina* has been interpreted variously as the grasping traces of nautiloid tentacles (Flower 1955) or as a feeding burrow (Osgood 1970). The association of *Skolithos*-like traces and these enigmatic vermiform burrows suggests a similar trace-maker for both.

?CRUZIANA

Description

Figure 10 represents a sandstone sole marking that consists of a series of raised elongate ridges in a V-shaped pattern. It is clear that the ridges on the sandstone sole are casts of a series of V-shaped grooves cut in an underlying muddy horizon, now removed by erosion. The V-angle formed by the ridges is approximately 90°. The trace as a whole is not markedly bilobate.

Interpretation

The V-shaped pattern of scratch marks deduced from the sole marking (Fig. 10) is broadly suggestive of the trace fossil *Cruziana*, but lacks the typical bilobed morphology of the ichnogenus. It is nevertheless possible that the scratch marks represent shallow furrowing of a trilobite-like arthropod. *Cruziana* traces are known from strata of Upper Precambrian to Triassic age (Häntzschel 1975: W55) and younger (Shone 1978).

HORIZONTAL TRACES ON UPPER BEDDING SURFACES

Description

Rare upper bedding surface exposures 45–50 m above the base of the Sardinia Bay Formation are covered by horizontal sand-filled burrows preserved in convex epirelief. These traces, shown in Figure 11, are up to 7 mm in diameter and 10 cm long, branch repeatedly, and cross one another. Raised stellate forms with burrows radiating from a central hub can also be recognized. Small, rounded, sand-filled tubes appear to intersect the bedding surface but their vertical extent has not yet been established.

Interpretation

These enigmatic trace fossils resemble *Chondrites*, their surface appearance corresponding to the three-dimensional tunnel patterns illustrated by Simpson (1956: 484, fig. 2) and Häntzschel (1975: W51, fig. 32 (1c)). The tendency of horizontal tunnels to cross one another is more typical of *Fucusopsis* (Upper Ordovician–Tertiary—Häntzschel 1975: W64) but the dichotomous branching and vertical tunnel sections weigh heavily in favour of *Chondrites* as the probable ichnogenus. *Chondrites* is known to occur in strata from Cambrian to Ter-

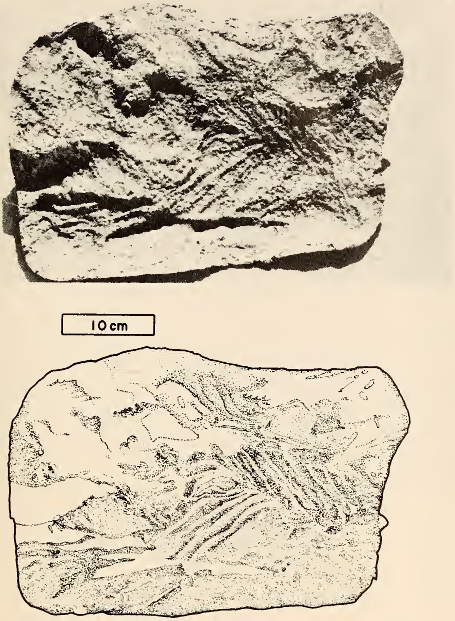

Fig. 10. Photograph (top) and tracing (bottom) of a fibreglass cast of a sandstone sole showing a series of ridges and grooves arranged in a V-shaped pattern. The general appearance is that of *Cruziana* but the trace is not markedly bilobed.

tiary in age, and is generally considered to be the feeding burrow of a sediment-eating animal (Richter 1927; Seilacher 1955; Osgood 1970).

PLANOLITES

Description

Short, gently-curved, subcylindrical burrows with rounded ends. The burrow fill is almost indistinguishable from the surrounding muddy substrate, so that the walls of individual traces are not clearly defined (Fig. 12). These mud-filled barely discernible tubes occur in the interval 60–73 m (see Fig. 2) in a dark pyritic mudrock unit, which weathers to a very light grey colour.

Interpretation

These traces resemble *Planolites* (Precambrian–Recent), which are believed to be burrows filled with the alimentary casts of sediment-ingesting animals,

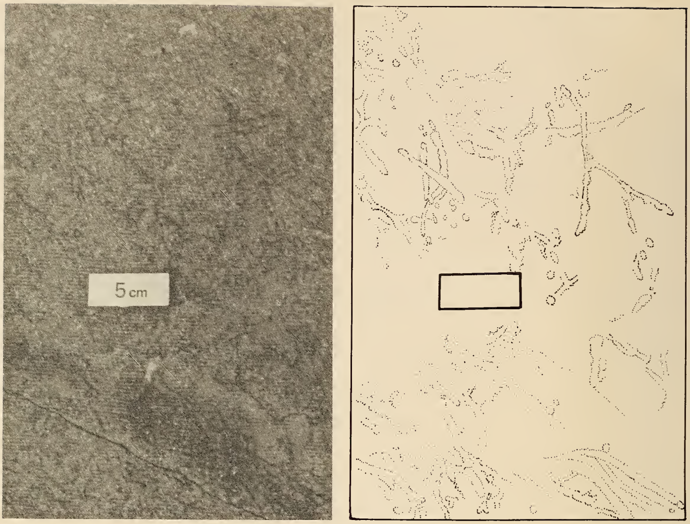

Fig. 11. Photograph (left) and tracing (right) showing thin horizontal sand-filled burrows and rounded cross-sections of vertical sand-filled tubes on a sandstone bedding surface. These traces are similar to *Chondrites*.

probably worms (Nicholson 1873; Häntzschel 1975: W95–W97). The indistinct walls suggest the host sediment and burrow-fill were identical in composition and that the burrowing activities may have taken place in a soupy mud (cf. Ekdale *et al.* 1984: 219).

ICHNOFACIES MODELS AND DEPOSITIONAL ENVIRONMENT

THE ICHNOFACIES CONCEPT

Trace fossil assemblages are often associated with particular depositional environments. Seilacher (1967) attempted to correlate trace fossil assemblages with water depth, but it is now clear that other factors (sediment composition and texture, temperature, light penetration, salinity, oxygenation, food supply, hydraulic energy, and sedimentation rates) play a significant role in the distribution of animals and their traces. Because each specific sedimentary environment is normally associated with a package of factors that controls the distribution of animals and the preservation of their traces in that environment, the development of ichnofacies models linking trace fossil assemblages with sedimentary facies (Frey & Pemberton 1984) seems entirely logical. It should be borne in

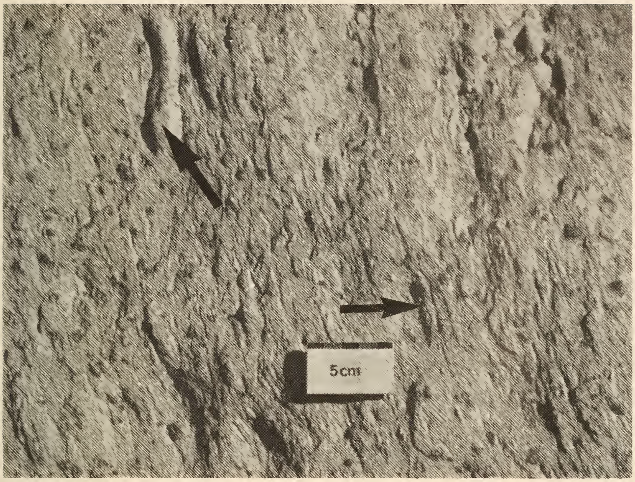

Fig. 12. Weathered surface of a mudrock unit showing disseminated pyrite now altered to limonite (dark nodules) and short, gently curved burrows with rounded ends (arrowed), which resemble *Planolites*. Note that the burrow fill is almost indistinguishable from the substrate; the burrow margins are revealed only by the effects of differential weathering.

mind, however, that ichnofacies models are likely to be less reliable in dealing with ancient sedimentary rocks than is the case in younger strata and sediments, where the organisms responsible for producing the traces can be more readily identified and their behaviour more easily correlated with changes in the governing conditions.

SKOLITHOS ICHNOFACIES

The *Skolithos* ichnofacies model described by Seilacher (1967) and Frey & Pemberton (1984: 198–199) is typified by the presence of burrows with reinforced wall linings and a predominance of vertical shafts. Characteristic ichnogenera are *Skolithos*, *Ophiomorpha* and *Diplocraterion*. The wall linings indicate burrowing in soft sediment. Sedimentary structures associated with this ichnofacies include near-horizontal lamination, ripple laminae, trough cross-bedding, and flaser-, wavy- and lenticular-bedding. Biogenic structures are subordinate. The *Skolithos* ichnofacies is believed to indicate high current and wave energy regimes in shallow marine settings, ranging from shallow shelf and shoreface to estuarine and tidal-flat environments.

CRUZIANA ICHNOFACIES

The *Cruziana* ichnofacies model (Seilacher 1967; Frey & Pemberton 1984: 199–200; Ekdale *et al.* 1984: 194–196) is typified by unconsolidated substrate at the time of bioturbation, and is indicative of moderate to low energy levels in shallow marine environments. *Cruziana*, *Thalassinoides*, and *Planolites* are characteristic trace fossils. Horizontal shafts predominate over vertical shafts, and the substrate tends to be totally bioturbated with few relict sedimentary structures.

TRACE FOSSIL ASSOCIATIONS IN THE SARDINIA BAY FORMATION

Three trace fossil associations can be distinguished in the Sardinia Bay Formation.

Association 1

This trace fossil association, which includes traces resembling *Ophiomorpha*, *Thalassinoides*, *Diplocraterion*, *Chondrites*, and possibly *Cruziana*, occurs in the interval 41–60 m (see Fig. 2). Sedimentary structures predominate over biogenic ones in this interval and are indicative of relatively high wave and current energy at the time of deposition. Both vertical and horizontal traces are present. Vertical components appear to be more abundant (see Fig. 3), and many of the burrows are lined with a dark pyritic sand. The pyrite is evidently diagenetic in origin (Shone 1983: 115) and could have formed in response to local reducing conditions associated with originally organic-rich linings.

Association 2

A second trace fossil association, consisting of *Planolites*-like traces in a dark pyritic mudrock, occurs in the interval 60–73 m (see Fig. 2). The apparent paucity of burrows and low faunal diversity suggest a fairly inhospitable environment. The presence of disseminated pyrite in this interval could indicate anoxic and possibly hypersaline conditions (Shone 1983), both of which might inhibit colonization by sediment-dwelling organisms.

Association 3

This association, which occurs in the Upper Sardinia Bay Formation in the interval 125–155 m (see Fig. 2), consists of intensely bioturbated muddy sandstones and siltstones in which traces resembling *Skolithos* and *Fascifodina* occur. There are few relict sedimentary structures. Burrowing appears to have taken place in unconsolidated substrate.

Discussion

None of the Sardinia Bay Formation trace fossil associations fit comfortably into the models proposed by Frey & Pemberton (1984). The first Sardinia Bay association (41–60 m) contains elements of both the *Skolithos* and *Cruziana* ichnofacies models, fitting best into the *Skolithos* ichnofacies despite the absence of *Skolithos* burrows and the presence of *Cruziana*-like traces. The third Sardinia Bay association (125–155 m) fits best into the *Cruziana* ichnofacies model but lacks *Cruziana* itself and is characterized by *Skolithos*! Both *Skolithos* and *Cruziana* ichnofacies models indicate a shallow marine origin for the Sardinia Bay strata but details of the ichnofacies models are poorly matched with details of the Sardinia Bay association.

The difference extant between the ideal ichnofacies models and trace fossil associations in the Sardinia Bay Formation could reflect broad aspects of the depositional environment. Detailed facies descriptions, interpretations, and palaeogeographic reconstructions have been described elsewhere (Shone 1983, 1987). The purpose of this paper is to document and describe the Sardinia Bay trace fossils. The proposed depositional model is, however, sufficiently unconventional to warrant brief consideration. The Sardinia Bay Formation is believed to have been deposited in a transgressing epeiric sea. Epeiric seas formed by flooding of intracontinental areas may have been quite common in the past. Their extreme shallowness over large areas may have led to frictional damping of tides and currents in inner epeiric shelf reaches (Shaw 1964; Irwin 1965; Hallam 1981), reducing circulation to the point where anoxic hypersaline conditions prevailed. The innermost shelf areas might therefore be characterized at best by a restricted biota, at worst by no biota at all. Mudrock units in the Sardinia Bay Formation containing disseminated pyrite, a possible indicator of anoxic and hypersaline conditions (cf. Berner *et al.* 1979), do in fact include very few identifiable trace fossils. What is puzzling, however, is the repeated superposition of trace-free mudrock units with bioturbated sandstones (see Fig. 2). Such rapid vertical facies changes are probably typical of epeiric sea deposits. Small fluctuations in relative sea-level might accomplish large lateral shifts in the boundaries of depositional environments, because of the extremely low bottom gradients involved. The repetition of certain facies (see Fig. 2), in particular the innermost shelf mud facies, could reflect small changes in relative sea-level.

The ichnofacies models proposed by Frey & Pemberton (1984) are based in part on more conventional sedimentation models.

The sedimentary structures in trace fossil association 1 indicate moderate wave and current activity, which could have been responsible for restricting both the number of sediment-dwelling organisms and the degree of bioturbation. The ichnofaunal diversity was not so restricted, however, which suggests that the sediments hosted a variety of animals during fair-weather periods. Association 1 could be representative of the zone of wave-break and unfettered tidal current flow in an ancient epeiric sea.

Association 2 (mudrock with barely discernible *Planolites* traces, disseminated pyrite) appears to have been deposited in a zone of restricted circulation. Increasingly anoxic conditions in such quiet reaches of an epeiric sea would eventually prohibit colonization by sediment dwellers and eliminate the possibility of soft-substrate burrowing.

Association 3 appears to have developed in an intermediate zone, where damping of tidal currents and open sea waves was only partial. Anoxic conditions could have arisen in this zone as a result of reduced circulation, and this could be reflected in the restricted ichnofauna (*Skolithos* and *?Fascifodina*). The extensive bioturbation that occurred probably indicates long-term burrowing in a low-energy environment in which ichnocoenoses were seldom displaced. Bedding traces formed here would have a very low preservation potential because of the high degree of bioturbation. This places *Skolithos* out of the high-energy clean-sand facies with which it is normally associated, but in other respects provides a far better explanation for the Sardinia Bay trace fossil associations.

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